On the feasibility of inferring the applied mechanical loading of a conveyor system test rig from monitored system parameters

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ABSTRACT

Conveyor systems are ubiquitous throughout industry, providing materials transfer functionality across a wide range of applications. High availability requirements coupled with flexible modes of operation demand that maintenance of systems be conducted as efficiently as possible. In this vein, this paper presents an investigation into the feasibility of observing the presence of mechanical loading via the responses of a range of monitored system parameters, with a view to understanding the relationship between system operation and health.

A test rig is used to enable the emulation an industrial conveyor system's dynamics, and a wide range of sensors are employed to enable a comprehensive parameter set to be observed. A range of mechanical loading mechanisms are used to replicate the presence of loads typically experienced by a conveyor system, and a number of test scenarios are conducted, comprising both isolated and combined loading scenarios.

It was observed that, when applied in isolation, the presence of axial, radial and torsional loads applied to the rig can feasibly be identified from the combined response of a unique subset of system parameters. However, as more complex modes of loading are introduced, both in terms of profile and combinations of loads, less clarity in responses can be observed, with significant cross-coupling of effects present, suggesting that isolating conveyor loading within an industrial environment is likely to require leveraging of a wide range of parameters and state-of-the-art signal processing techniques.

Keywords: condition monitoring, maintenance, diagnostics, conveyor systems, sensors

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1. INTRODUCTION

Conveyor systems are fundamental industrial assets, which, at the highest level, serve to provide the function of material transfer. Their typically simple design and construction enables use throughout a wide range of industrial applications, with lengths ranging from a few metres to kilometres. This utility enables single systems to potentially be utilised for multiple, different purposes throughout its operational life, resulting in exposure to a wide range of loading conditions, potentially beyond those within their design envelope.

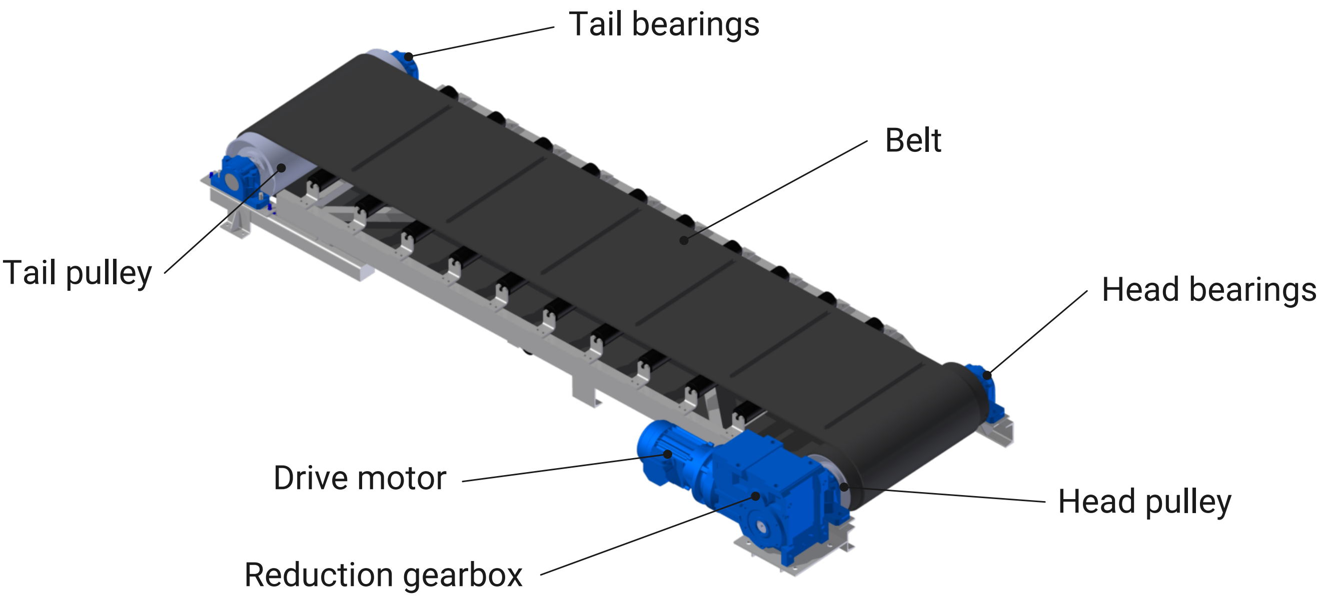

Figure 1: Layout of typical industrial conveyor system, with major components labelled

Such variation in operational conditions will likely have implications for the form and frequency of maintenance activities required to support continued operation of a system. With systems typically subjected to very high utilisation demands and having severe penalties associated with lost operational time, it is key that maintenance activities can be planned and conducted efficiently, ensuring that only minimal downtime be incurred.

As such, there is a need to understand how the loading a conveyor system is subjected to during operation impacts upon the long-term health of the system. Accordingly, this paper presents the findings from a body of testing completed to characterise the response of system parameters to a range of loading conditions, using a bespoke test rig as a proxy for an industrial conveyor system.

A wide range of system parameters are selected for continuous monitoring throughout testing, to enable an evaluation of each's potential a proxy for indicating the presence and magnitude of applied loads, with a view to informing the specification of an industrial conveyor monitoring system.

2. METHODOLOGY

2.1. Conveyor Emulation Rig

To enable the characterisation of conveyor parameter responses to various loading scenarios a conveyor emulation rig (CER) was designed and constructed, allowing the dynamics of a typical industrial conveyor system to be replicated in a controlled environment. Within the CER a series of loading mechanisms are incorporated, enabling the application of axial, radial and torsional loading, either in isolation or simultaneously.

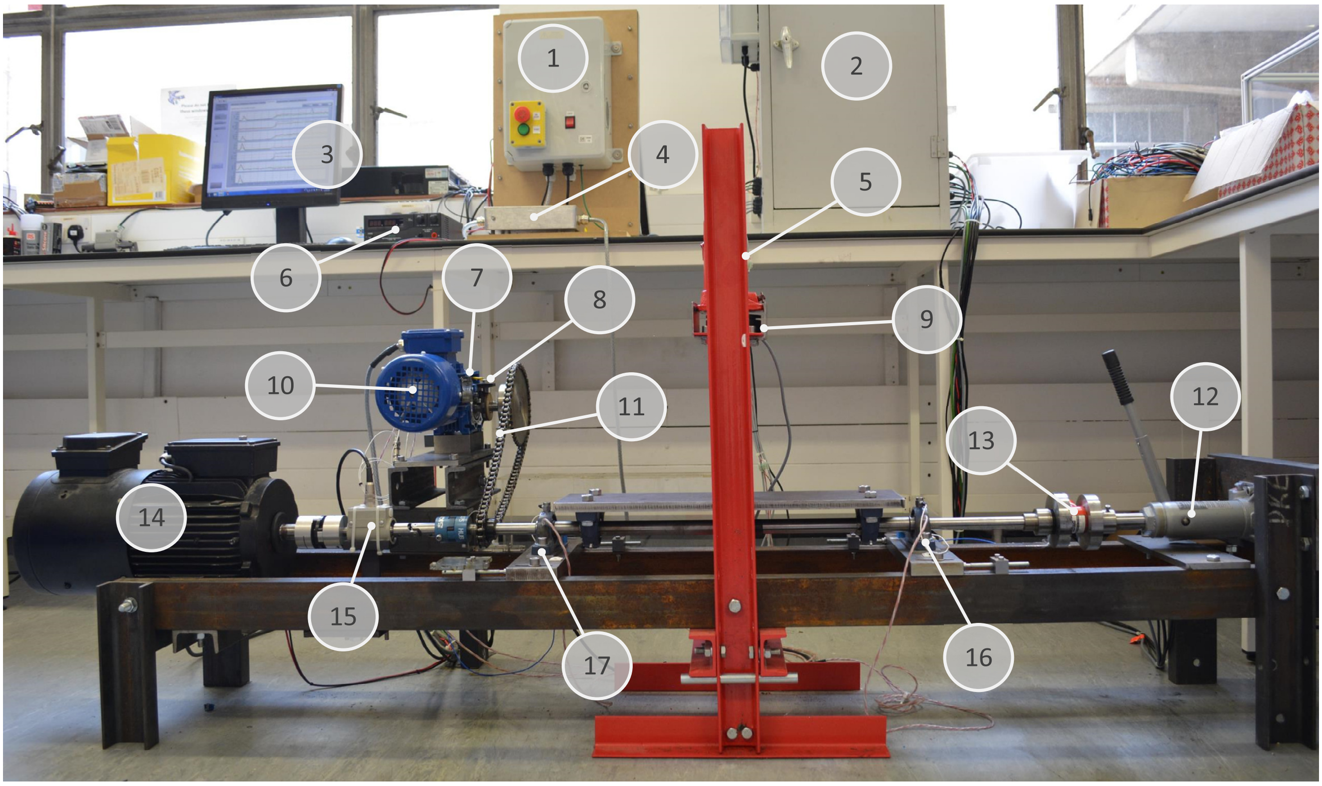

Figure 2: Overview of CER: 1 - VFD box; 2 - DAQ cabinet; 3 - Control PC and HMI; 4 - Power monitoring; 5 - Radial jack; 6 - DC injection power supply; 7 - Gearbox; 8 - Speed sensor; 9 - Radial loadcell; 10 - Drive motor; 11 - Drive chain; 12 - Axial jack; 13 - Axial loadcell; 14 - Braking motor; 15 - Torque transducer; 16 - Bearing 2; 17 - Bearing 1

A body of failure mode and effect analysis (FMEA) was conducted based upon an industrial conveyor system, enabling loads typically experienced by such a system to be identified, from which CER scenarios could be designed to enable the replication of these. It should be noted that the mechanisms of belt failure are not the focus of this research at present, therefore the CER omits a belt and instead uses the various loading mechanisms to emulate the presence of a belt.

Axial and radial loads are applied using dedicated hydraulic jacks, actuated manually, whilst torsional load is applied via a second braking motor, where the principles of direct current (DC) injection braking are employed. The strength of the torsional load generated is controlled by modulating the amplitude of the DC injected, thus by employing a programmable power supply more complex torsional load profiles can be generated e.g. saw tooth, quasi-sinusoidal.

Table 1: Summary of CER instrumentation

<table>
<tr><th></th><th>Monitored parameter</th><th>Sensor</th><th>Signal conditioning</th><th>Acquisition unit</th><th>Acquisition rate</th><th>Continuous / Periodic</th></tr>
<tr><td rowspan="4">Drive motor</td><td>Line voltages (VAB and VCA)</td><td>LEM LV25-P</td><td>Custom LP filter and amplifier unit</td><td>NI USB6211</td><td>10kHz /phase</td><td>C</td></tr>
<tr><td>Phase currents (IA and IB)</td><td>LEM LA25-NP</td><td>Custom LP filter and amplifier unit</td><td>NI USB6211</td><td>10kHz /phase</td><td>C</td></tr>
<tr><td>Casing temperature</td><td>PT100</td><td colspan="2">Industrial Interface E100</td><td>2Hz</td><td>C</td></tr>
<tr><td>Vibration</td><td>Dytran 3255A2</td><td colspan="2">NI 9234</td><td>50kHz</td><td>P</td></tr>
<tr><td rowspan="4">Gearbox</td><td>Output shaft speed</td><td>Honeywell 103SR13A-1</td><td>NA</td><td>NI USB6211</td><td>Counter input</td><td>C</td></tr>
<tr><td>Casing temperature</td><td>PT100</td><td colspan="2">Industrial Interface E100</td><td>2Hz</td><td>C</td></tr>
<tr><td>Audible noise</td><td>Bruel & Kjaer type 4117</td><td colspan="2">NI 9234</td><td>50kHz</td><td>P</td></tr>
<tr><td>Acoustic Emission</td><td>Mistras WD</td><td>Mistras 2/4/6C voltage amplifier</td><td>NI PCI9251</td><td>1MHz</td><td>P</td></tr>
<tr><td rowspan="3">Bearing 1</td><td>Casing temperature</td><td>PT100</td><td colspan="2">Industrial Interface E100</td><td>2Hz</td><td>C</td></tr>
<tr><td>Vibration</td><td>Dytran 3255A2</td><td colspan="2">NI 9234</td><td>50kHz</td><td>P</td></tr>
<tr><td>Audible noise</td><td>Bruel & Kjaer type 4117</td><td colspan="2">NI 9234</td><td>50kHz</td><td>P</td></tr>
<tr><td rowspan="3">Bearing 2</td><td>Casing temperature</td><td>PT100</td><td colspan="2">Industrial Interface E100</td><td>2Hz</td><td>C</td></tr>
<tr><td>Vibration</td><td>Dytran 3255A2</td><td colspan="2">NI 9234</td><td>50kHz</td><td>P</td></tr>
<tr><td>Audible noise</td><td>Bruel & Kjaer type 4117</td><td colspan="2">NI 9234</td><td>50kHz</td><td>P</td></tr>
<tr><td>Radial jack</td><td>Applied load</td><td>Tedea Huntleigh TH220</td><td>Soemer LAC65.1 amplifier</td><td>NI USB6211</td><td>1Hz</td><td>C</td></tr>
<tr><td>Axial jack</td><td>Applied load</td><td>Novatech F210</td><td>Vishay Nobel AST 3IS</td><td>NI USB6211</td><td>1Hz</td><td>C</td></tr>
<tr><td rowspan="2">Braking motor</td><td>Output power</td><td>Manson HCS-3302-USB</td><td colspan="2">NA</td><td>2Hz</td><td>C</td></tr>
<tr><td>Applied torsional load</td><td>HBM T5</td><td>Vishay Nobel AST3IS</td><td>NI USB6211</td><td>1Hz</td><td>C</td></tr>
<tr><td>Environment</td><td>Ambient temperature</td><td>PT100</td><td colspan="2">Industrial Interface E-100</td><td>2Hz</td><td>C</td></tr>
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To enable potential indicators of load to be explored a wide range of sensing is included within the CER (table 1). Monitored parameters were selected based upon a review of both extant literature as well as technical standards, enabling those parameters expected to present most sensitivity to load to be identified, whilst considering implementation factors such as cost and complexity also.

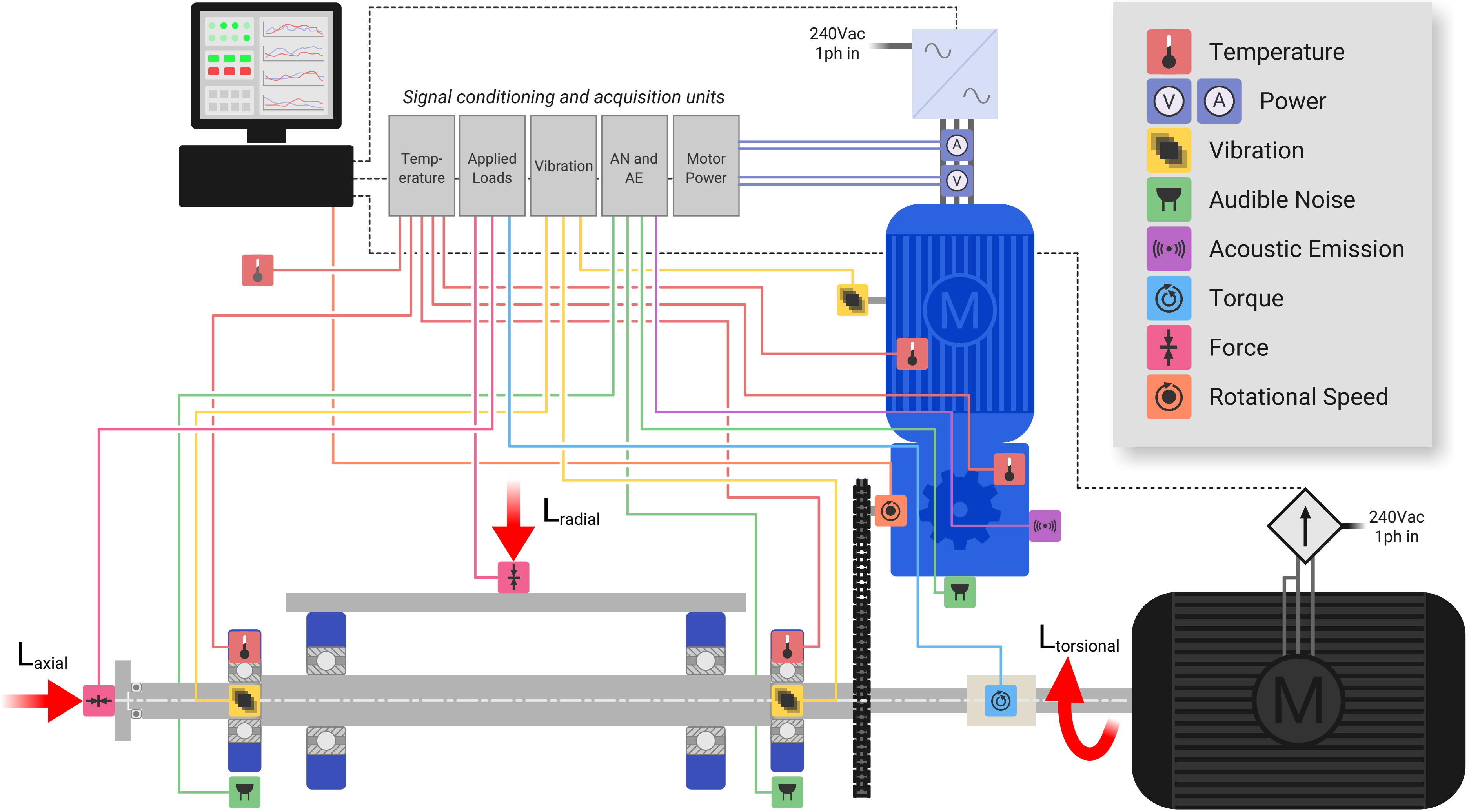

Figure 3: CER instrumentation schematic

2.2. Testing Regime

A total of 5 loading scenarios were investigated on the CER: axial only, radial only, torsional only, axial and radial, radial and braking. For axial and radial loads step profiles were applied only, while for torsional loads both step and square-wave profiles were applied, with the magnitudes in table 2 used for each.

Table 2: Summary of magnitudes of test variables used

Variable	Abbrev.	Step 1	Step 2	Step 3
Axial Load (kN)	A	2	4	6
Radial Load (kN)	R	1	2	3
Torsional Load (Adc)	T	2	5	8

After the application of each loading magnitude monitored parameters were allowed to reach steady state values prior to the application subsequent steps. In total, each scenario was conducted 3 times to enable the repeatability of observations to be investigated.

3. Results

3.1. Isolated Loading Scenarions

When an axial load is applied to the CER in isolation the rotational speed of the gearbox output shaft reduces by approximately 1rpm per 2kN step of load. A corresponding increase in power consumption is not seen; with the VFD operating in open-loop V/f mode no attempt to compensate for the increased load on the drive is made.

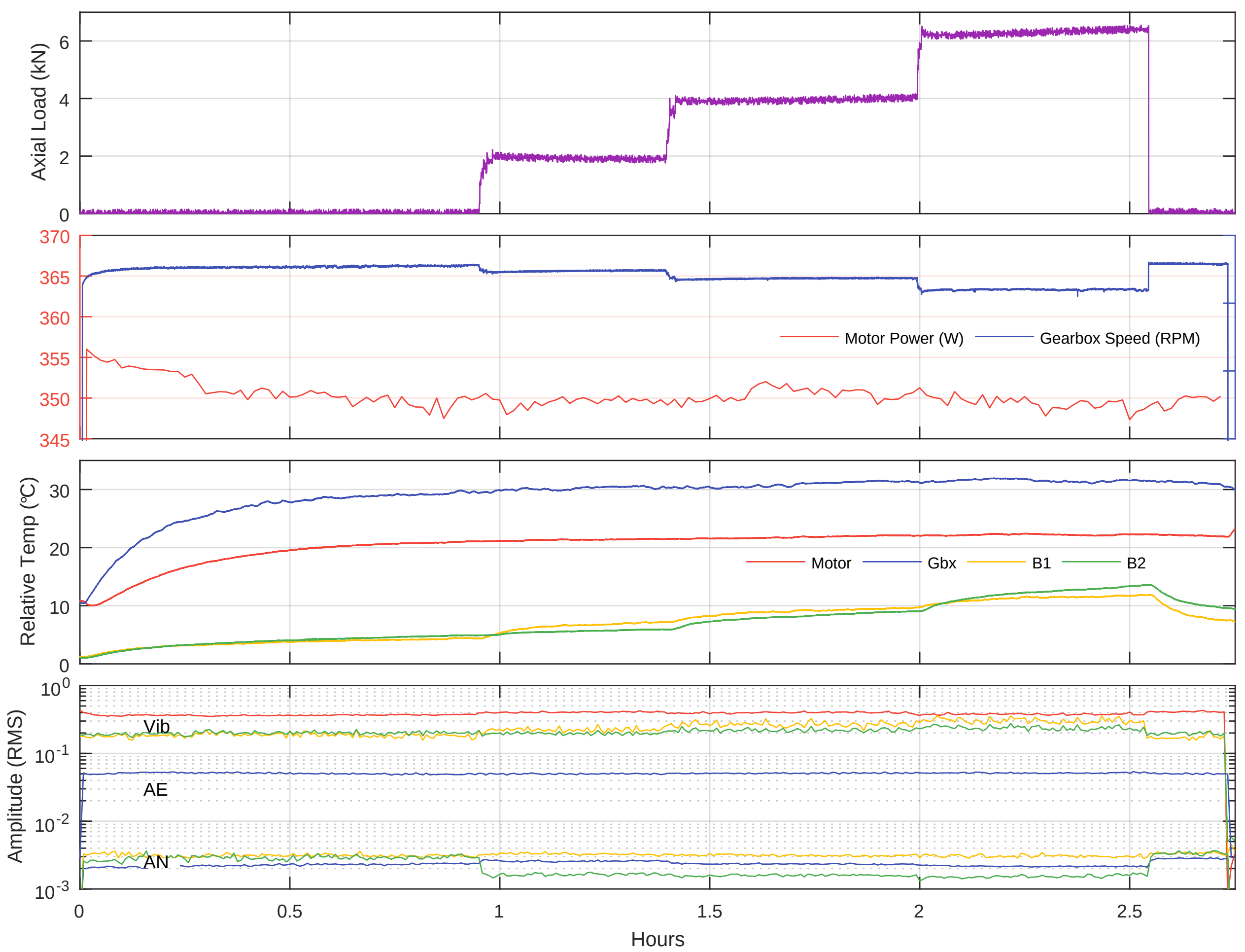

Figure 4: Axial loading characterisation test scenario

In general, little change is seen in motor and gearbox parameters in response to axial load. Vibration, audible noise and acoustic emission RMS values present minimal sensitivity to axial load, and the temperatures of each show only small increases from no load to maximum.

Drive bearings present more significant sensitivity to axial load; the vibration RMS values of both Bearing 1 and 2 show a clear increase corresponding to each load step applied, and the audible noise RMS value of Bearing 2 shows a sharp reduction as load is applied. The temperature of each bearing also increases in response to greater load. Initially, at steps 1 and 2 the absolute temperature of bearing 1 exceeds bearing 2 by 1-2°C, as a result of bearing 1 supporting the majority of the axial load. However, as step 3 is applied the temperature of bearing 2 can be seen to exceed bearing 1. This observation can be explained by the design of the CER; axial load is applied via a thrust bearing to minimise parasitic torsional load. Increasing the load subjected to the thrust bearing causes a greater level of heat to be generated, with thermal images suggesting a casing temperature of 70°C at 6kN (fig. 5). This added heat is conducted down the drive and thus over time causes an 'artificial' increase in the temperature of bearing 2, which lies in closest proximity.

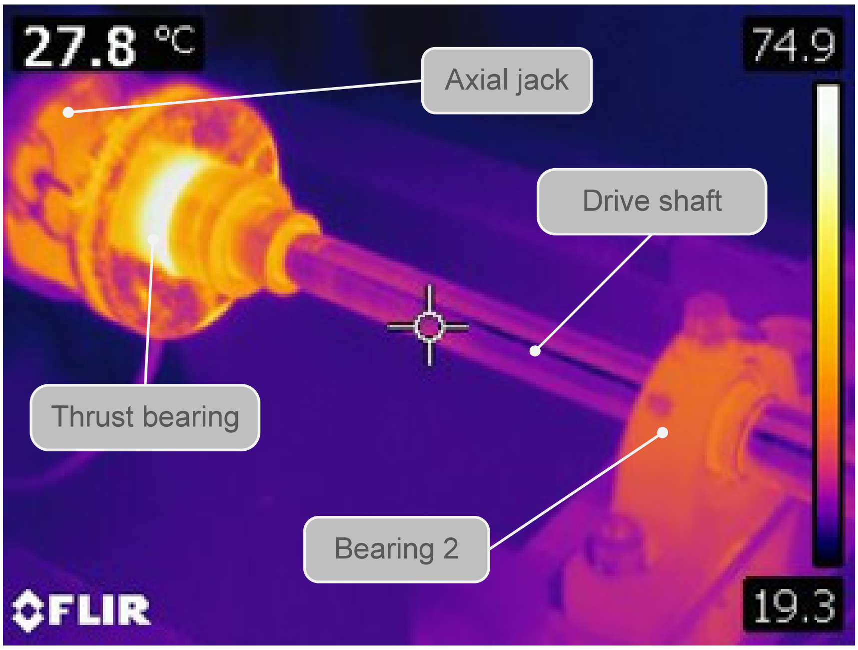

Figure 5: Thermal image of drive shaft and axial loading location during the application of 6kN axial load - note maximum scale temperature of 74.9°C

Similarly to the application of axial load, when radial load is applied in isolation the CER motor and gearbox show minimal sensitivity; due to the chain drive configuration employed, axial and radial loads are not reacted significantly by the drive elements of the CER. No significant response to radial load can be observed in motor and gearbox speed, power consumption, temperature, RMS vibration or RMS acoustic emission across the applied range (fig. 6).

In contrast, both drive bearings show significant sensitivity to radial load, with both present increased levels of AN RMS across the range. This is likely a consequence of a slackening effect on the chain, caused by deflection of the driveshaft in response to radial load. Bearing 1 can be seen to present a greater magnitude RMS value, likely as a result of its proximity to the drive chain. Both bearings also show an decrease in temperature under radial load, with Bearing 1 reducing by 1°C and Bearing 2 by 2-3°C, and a small increase in vibration RMS amplitude.

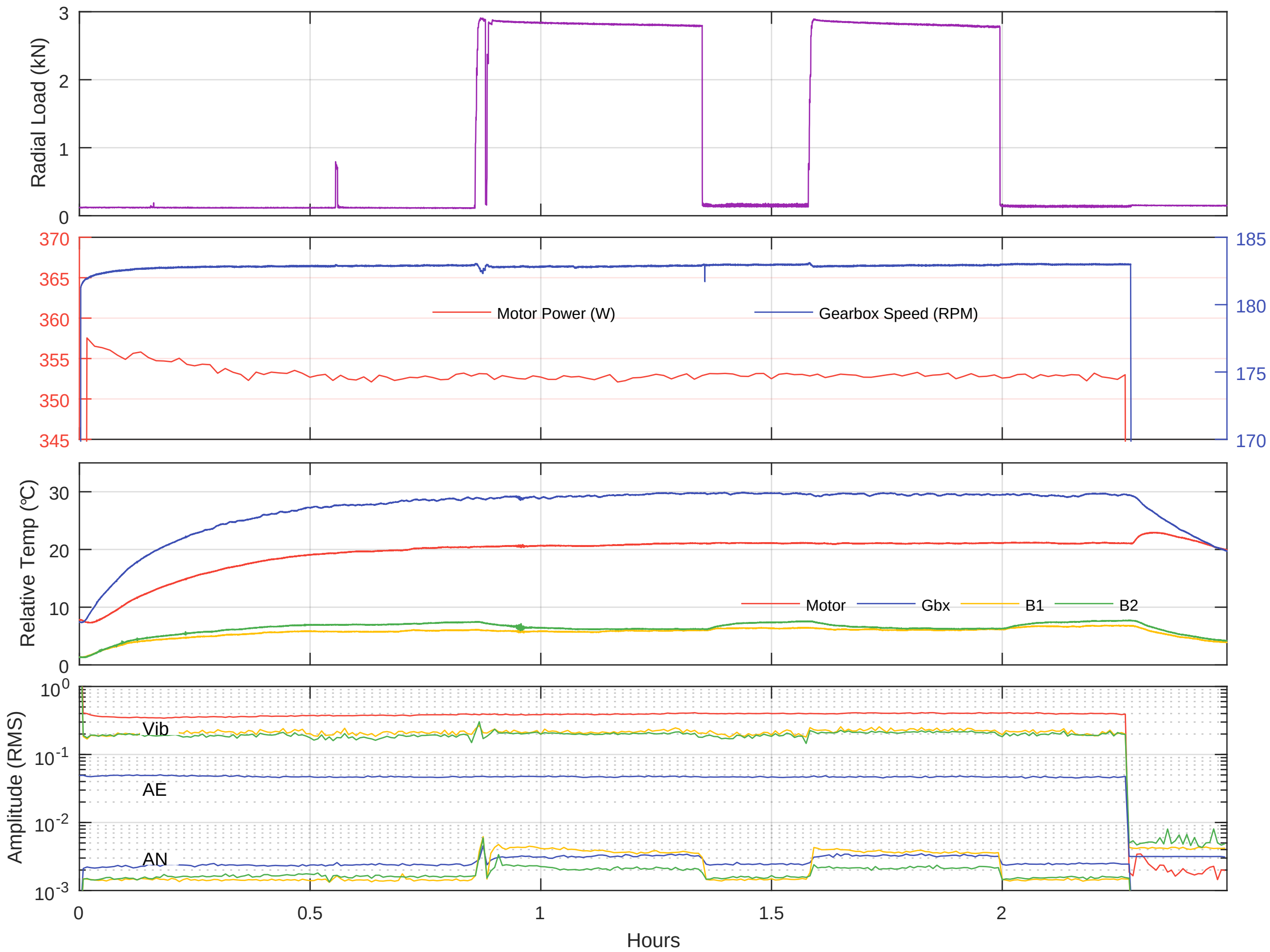

Figure 6: Radial loading characterisation test scenario

When torsional load is applied to the CER it is reacted primarily by the motor and gearbox, resulting in an observed simultaneous decrease in speed and increase in power consumption of 5rpm and 15W respectively at 2Nm load. Additionally, motor vibration RMS and gearbox AE and AN RMS values can also be seen to decrease as torsional load is applied, likely as a result of the reduction in operating speed.

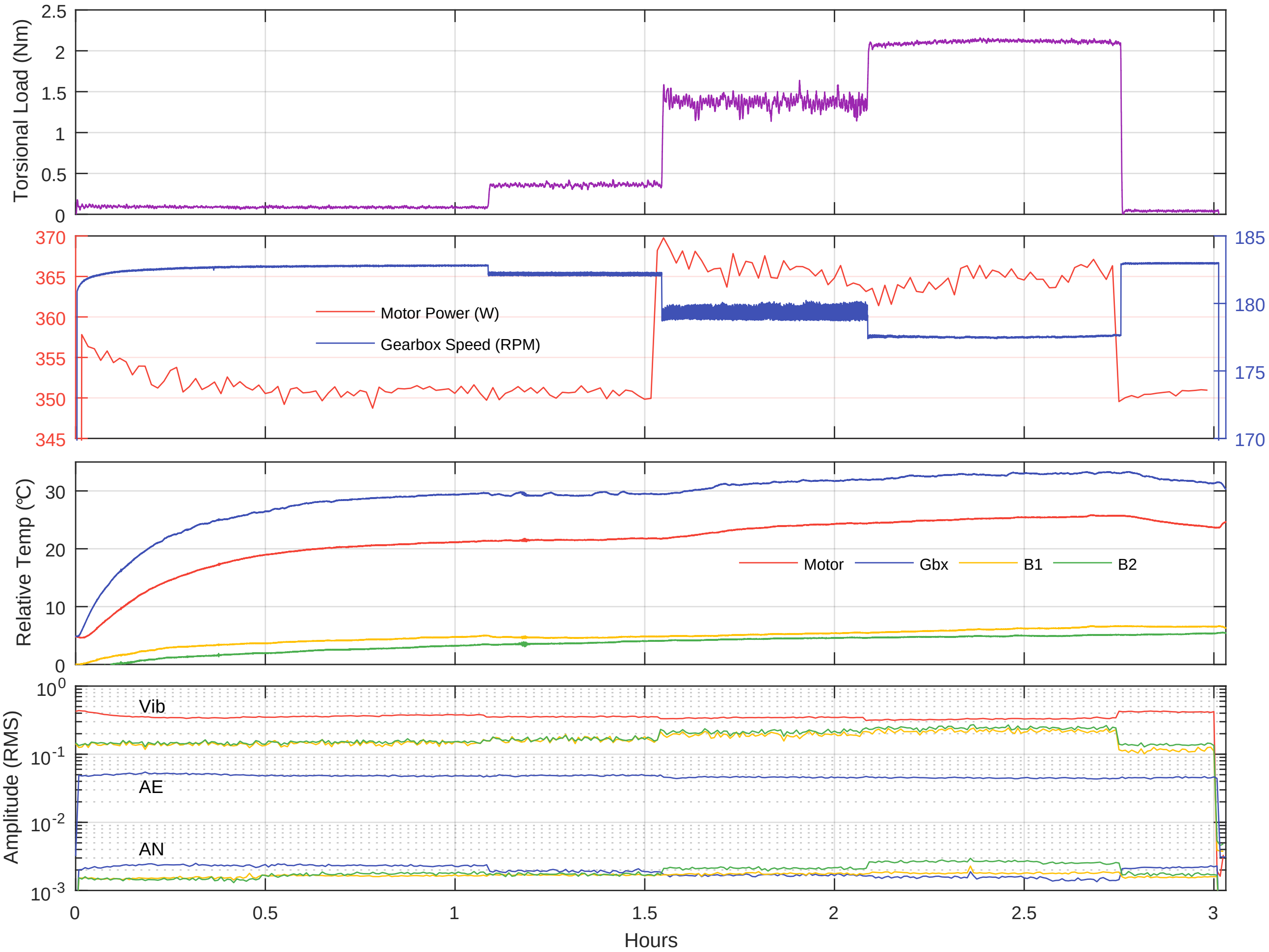

Figure 7: Torsional loading characterisation test scenario

No significant response to torsional load can be observed in the temperature of the drive bearings. Both do however show increased vibration and AN RMS values, likely caused by the slackening of the drive chain in response to the presence of counter-torque, resulting in Bearing 1 AN RMS being greater than that of Bearing 2 (fig. 7).

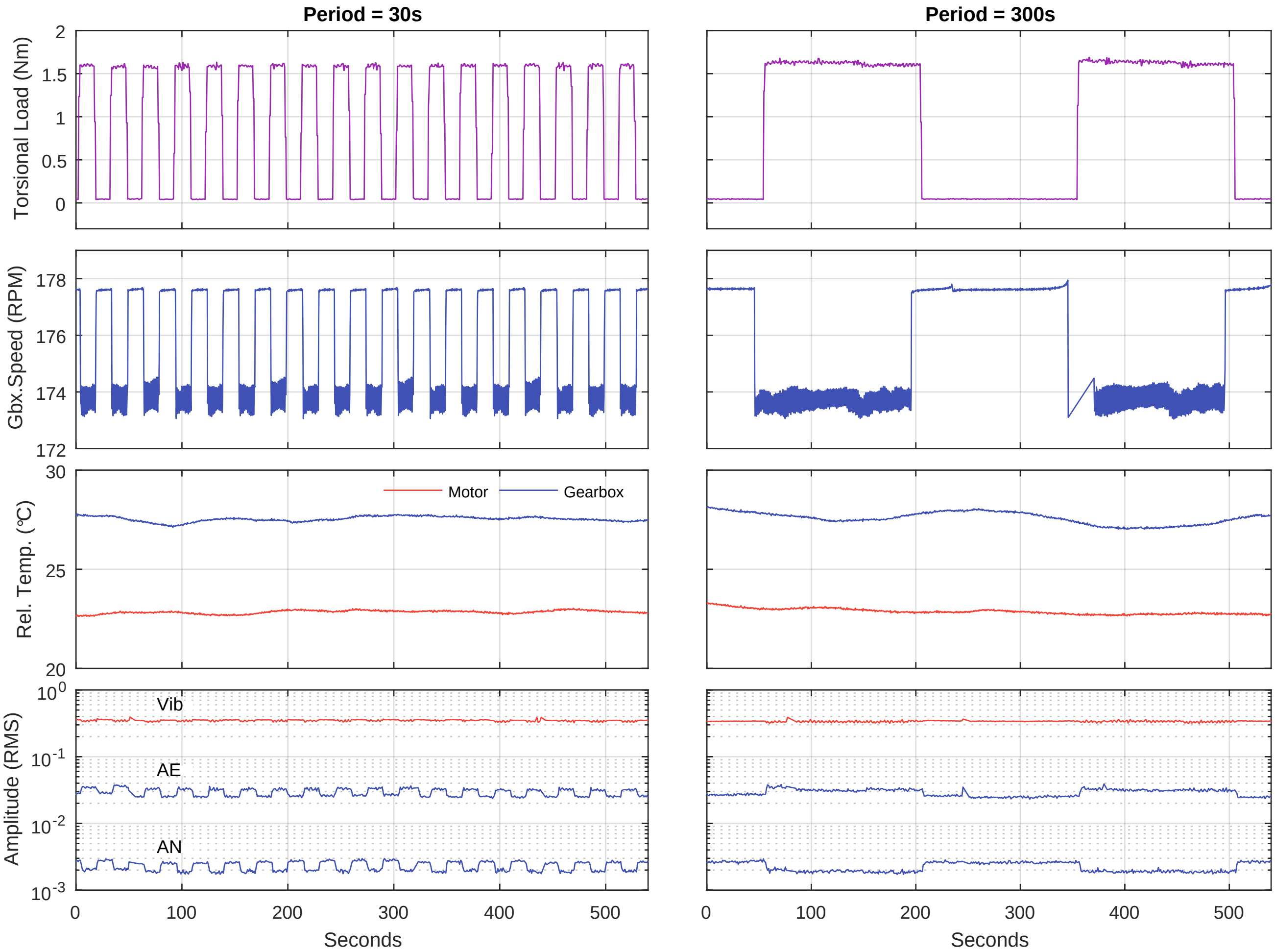

Figure 8: Torsional square-wave loading characterisation test scenario

3.2. Combined Loading Scenarios

When the CER is subjected to both axial and radial load simultaneously, as with isolated loading, motor and gearbox parameters present little sensitivity. A small reduction in power consumption and rotation speed is observed, along with minimal change in motor and gearbox vibration, AN and AE and temperature parameters.

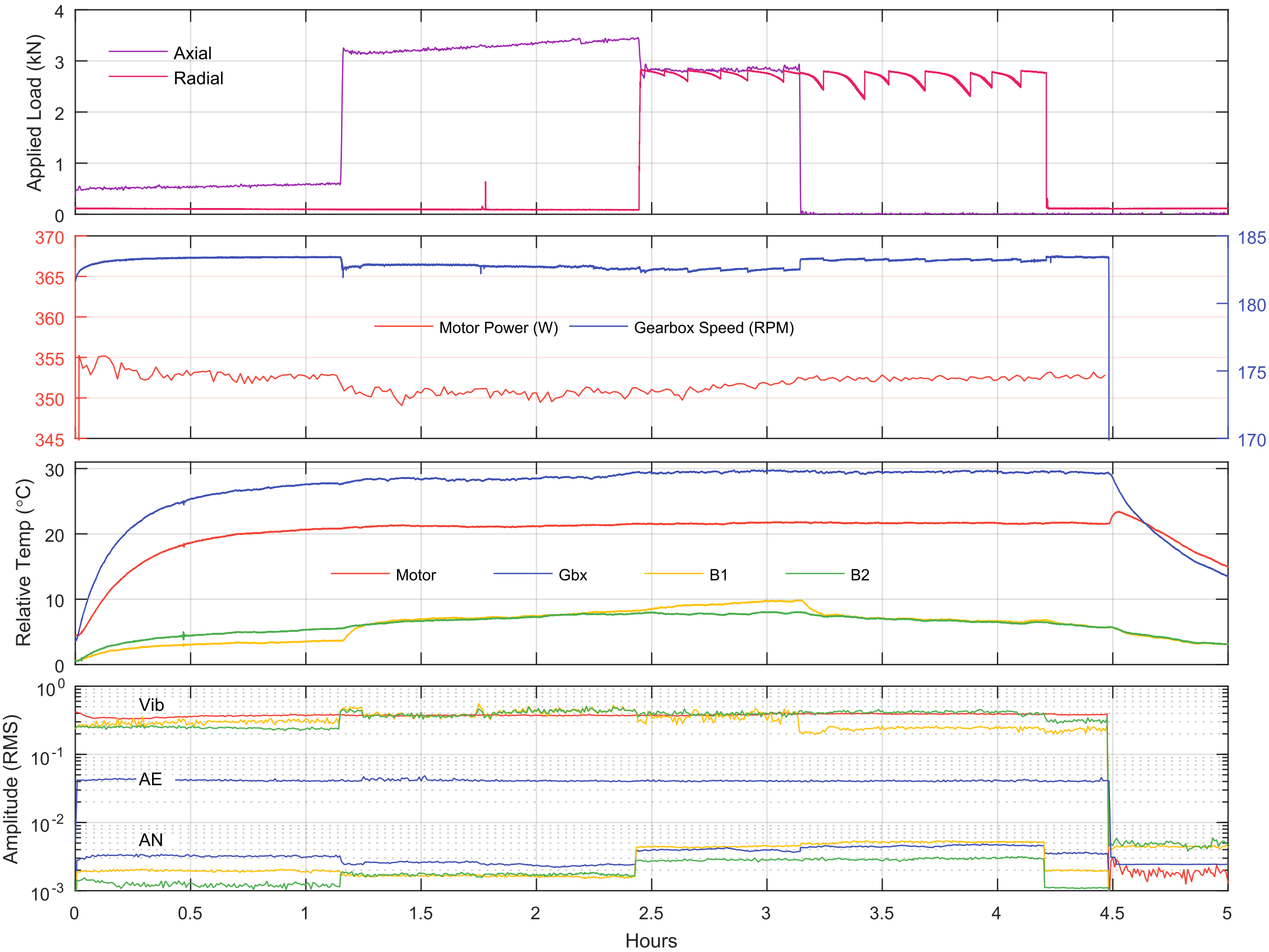

Figure 9: Combined axial and radial loading characterisation test scenario

As with isolated axial loading, initially after axial load has been applied the temperature of Bearing 1 increases whilst Bearing 2 remains relatively unchanged. However, when radial load is applied in addition to axial load the temperature of Bearing 2 begins to fall, as previously observed during isolated radial tests, whereas the temperature of Bearing 1 continues to increase until axial load is removed, after which Bearing 1 temperature falls also. Similarly, the vibration RMS values of the drive bearings present sensitivity to both modes of loading without an obvious trend. Initially, both bearings increase as the applied axial load is increased, however both fall as radial load is applied. As axial load is removed Bearing 1 falls to a level below that seen prior to the application of any load, whereas Bearing 2 shows little change, and when finally radial load is removed both values decrease further.

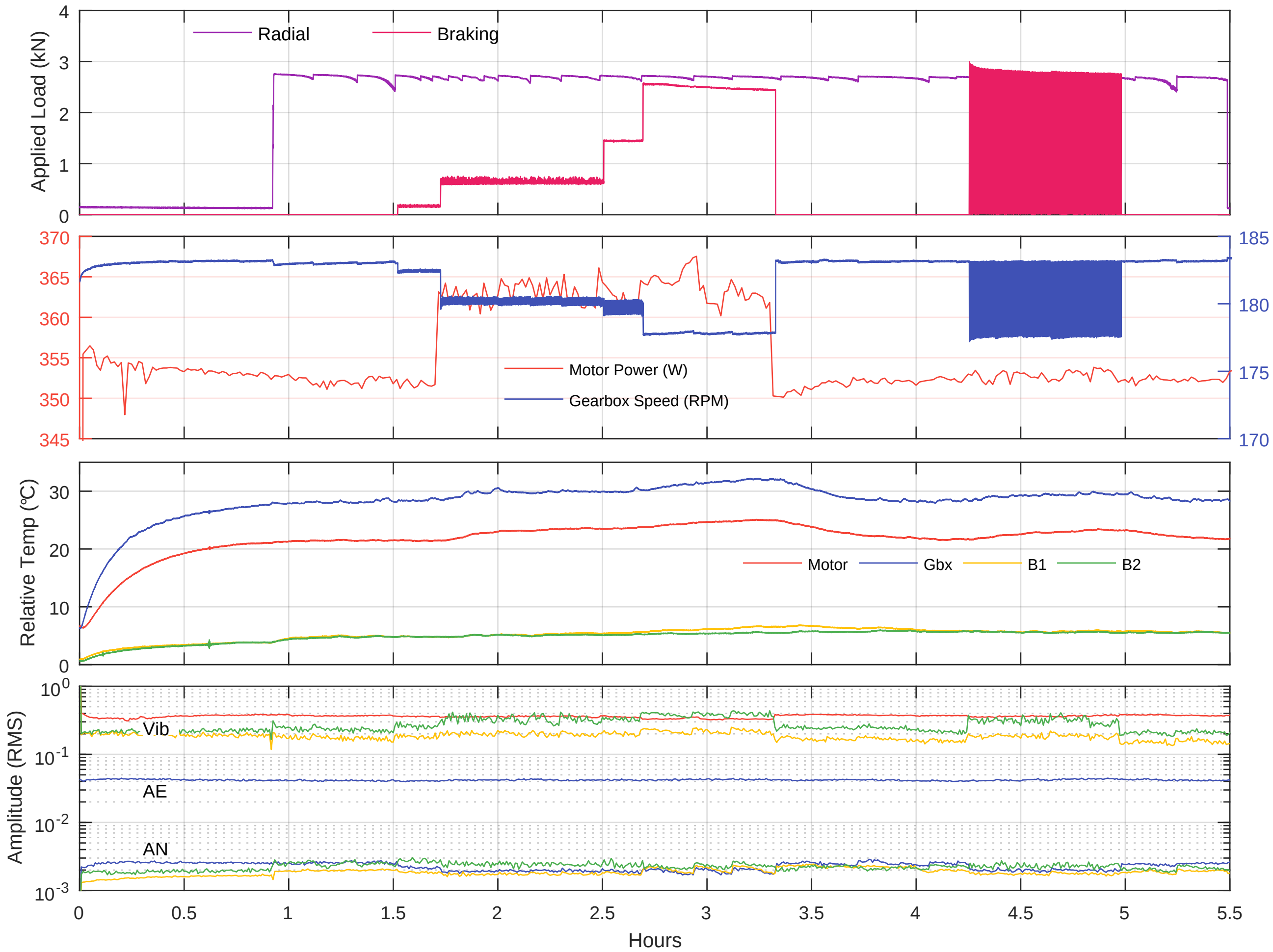

Figure 10: Combined radial and braking loading characterisation test scenario

A combination of radial and braking load applied to the CER results in a reduction in rotational speed of 5RPM at 2.5 kN of radial and 2.5Nm of torsional load, a similar reduction to that observed during isolated torsional load. Power consumption is increased also, however by a slightly lower magnitude than isolated torsional. The temperature of the motor and gearbox presents little sensitivity to radial loading, but when subjected to maximum torsional load increases by 4° C, again similar to isolated torsional loading. However, drive bearing temperatures do not present a reduction in response to radial load as previously observed, with a small increase in both seen when torsional load is applied. Motor vibration RMS and gearbox AE RMS present minimal sensitivity to combined radial and torsional loading, whilst gearbox AN RMS does show sensitivity, however no clear trend can be observed. The vibration RMS value of both bearings does present a significant increase in response to both modes of loading, with the magnitude of both exceeding levels observed during isolated loading. Similarly to gearbox AN RMS, bearing AN RMS values show sensitivity to both modes of loading applied simultaneously, however no clear trend can be observed.

4. DISCUSSION

Data acquired during operation of the CER suggests that, when applied in isolation, the presence and form of loading can feasibly be inferred via the combined response of specific system parameters (table 3).

Table 3: Summary of sensitivity of parameters to applied loading profiles

Applied Loading	Sensitive parameters	Response
Axial	B1 temp, B2 temp, B1 vib, B2 vib, B2 AN,	Bearing temperature and vibration RMS differential present - B1 greater than B2. Reduced B2AN RMS under load
Radial	B1 temp, B2 temp, B1 AN, B2 AN	Decrease in absolute temp and increase in AN RMS of both B1 and B2
Torsional	Motor temp, gbx temp, motor vib RMS, gbx AN and AE RMS, motor power, gbx speed	Increased power drawn with decreased gbx speed. Increases in all other parameters

Whilst in certain scenarios individual parameters can be able to indicate the presence of abnormal loading, by leveraging information from multiple parameters a greater degree of confidence in inferences can potentially be realised. For example, a change in operational condition due to an observed change in rotational speed can be detected directly from a single parameter, however, the root cause of this change may be radial or torsional loading. Only by considering the response of additional parameters such as power consumption and component temperatures can a more detailed inference be made, suggesting that more comprehensive sensing capability could support greater inferencing and confidence therein.

However, whilst these combinations of responses have presented potential as indicators of loading, the strength of the response of each varies significantly. Some have presented clear, quantifiable changes in response to the application of a loading condition, whereas others can only be considered as qualitative indicators of a change in operational conditions, with a lack of obvious, repeatable trends. As such, the level of inference potentially possible varies across the range of conditions.

Additionally, when multiple loading conditions are applied simultaneously, the ability to identify clearly each mode from the parameters available is reduced. Whilst changes in operation can be observed as loading conditions are changed, effects appear typically to be coupled, and as a result responses are not necessarily a summation of the responses observed during isolated loading.

As it's currently designed the CER can be seen to decouple the effects of certain loading conditions due to the physical layout of components. By driving the main shaft via a chain axial and radial loads applied are not significantly reacted by the motor and gearbox. Typically, an industrial conveyor system would be configured with a direct connection between the gearbox output and the head pulley, therefore it can be expected that in an industrial setting the response of components to loading may be even more tightly coupled than observed on the CER.

To attempt to decouple modes of loading, and thus enable isolation of individual modes of loading, additional system information accessed via signal processing techniques may provide value. For example, currently only time-domain analysis of parameters has been investigated, a large body of frequency-domain techniques are present within literature which may be able to provide valuable insight (see [1] for an overview). Alternatively, system parameter observability could be increased, supporting more detailed inferences, however, the impact of increasing DAQ hardware in an industrial setting must be considered. Additional hardware possesses an associated cost, both financial as well as in terms of system complexity and thus potentially reliability [2, 3], therefore the specific value of the information provided by each monitored parameter in supporting inferencing must be well understood.

However, ultimately techniques could, in the context of industrial conveyor systems, be used to support real-time monitoring of conveyor loading, with a view to enabling intelligent scheduling of PPM intervals, based upon the cumulative loading subjected to a system, as opposed to time in operational. Actions could be triggered upon the exceeding of thresholds, the levels of which could be determined empirically initially, however, to mitigate the potential issues associated with defining appropriate thresholds [4, 5, 6] a more sophisticated and automated process may ultimately be required.

5. CONCLUSIONS

Data acquired during operation of the CER suggests that modes in isolation can feasibly be identified using specific combinations of parameter responses. Whilst individual parameter responses do, in some cases, present sensitivity to specific loading modes, greater confidence in inferences can potentially be achieved through the utilisation of information from multiple parameter responses in conjunction.

Additionally, as the complexity of loading was increased identifying each mode present proved increasingly challenging, with cross-coupling effects impacting the clarity of responses. To address this challenge it was suggested that increasing the range of parameters monitored, facilitated by either additional data acquisition hardware or advanced signal processing techniques, could support greater observability of responses to loading.

Accordingly, it can be concluded that further testing is required in order to improve understanding of the operational characteristics of the CER, as well as associated indicators, ultimately leading to the development of an approach to real-time monitoring of conveyor system loading ready for trialling within an industrial environment.

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